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13. ABSTRACT *(Maximum 200 words)*

This report describes the acquisition and utilization of instrumentation in the support of high power microwave (HPM) research. Recent advances in understanding the output of intense beam-driven relativistic requires both highly temporally resolved measurement capabilities, coupled with signal processing techniques such as time-frequency analysis. In particular, better understanding of nonlinear effects such as mode-hopping due to the cross-excitation instability, required the ability to resolve frequency shifts during the generation of HPM radiation. The instrumentation acquired under this FY'99 DURIP grant led to the careful diagnosis of this instability.

14. SUBJECT TERMS
High Power Microwaves, HPM, BWO, mode-hopping, cross-excitation instability, time-frequency analysis

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The University of New Mexico

Pulsed Power and Plasma Science Laboratory

DURIP-99 FINAL REPORT

Refined Measurement and Signal Analysis Techniques in Vacuum and Plasma-Filled High Power Microwave Sources

(Grant No. F49620-99-1-0162)

15 June 2000

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Abstract

This final report describes the acquisition and implementation of instrumentation purchased under the auspices of the FY'99 DURIP program. All of the microwave diagnostic instrumentation have been purchased, installed, and used to perform refined measurements and signal analysis in a high power backward wave oscillator (BWO) experiment. The results of this measurement have been documented in a journal publication, "Studies of Relativistic Backward Wave Oscillator in the Cross-Excitation Regime," by F. Hegeler, M. Partridge, E. Schamiloglu, and C.T. Abdallah, *IEEE Transaction on Plasma Science Eighth Special Issue on High Power Microwave Generation*, June 2000.

The purpose of the acquired instrumentation was to carry out sophisticated frequency measurements in intense electron beam-driven high power microwave (HPM) sources to find new regimes of operation. We performed the first experimental measurements of the so-called "cross-excitation" regime in a high power backward wave oscillator. This regime allows simultaneous operation of two axial modes at different frequencies. It is a rich area of nonlinear physics that needs to be further explored, and it may prove useful to future HPM effects studies.

In addition, electrical engineering undergraduate and graduate students in the newly constructed Microwave Teaching Laboratory use most of the microwave equipment.

Description of Instrumentation

The instrumentation purchased under this grant were:

1. Hewlett-Packard Co. ($126,910.20):
   Purpose: Microwave instrumentation for the backward wave oscillator.
   HP8720D network analyzer with Opt. 010, 1CP, W50, and W52, HP85052C 3.5 mm precision calibration kit, and HP85131F flex port cables, HP83752B high power synthesized microwave sweeper with Opt. W30 and W32, HP4263B LCR meter with Opt. 001 and 002, and HP16089B test leads, HP 8714ES RF network analyzer with Opt. W32, and HP85032E calibration kit, and various microwave components (HP11581A, HP11667A, HP11667B, HP8120-4781, and HP8120-6469).
2. Tektronix Inc. ($31,837.73):
   Purpose: 3 GHz oscilloscope for microwave data acquisition.
   TDS694C Oscilloscope with 01100-5902, -6002, and 6902 attenuators.
3. Scientific Sales Assoc., Inc. ($28,477.15):
   Purpose: Vacuum leak detector for vacuum improvements of the high power microwave source.
   Varian D9790035UT120 vacuum leak detector with accessories.
4. Picosecond Pulse Labs, Inc. ($8,246.00):
   Purpose: 45 ps risetime trigger for the microwave data acquisition system.
   4050B pulse generator with accessories (model # 5331 and 5520C).
5. Gateway 2000 ($4,383.00):
   Purpose: Computer for microwave simulations and data collection from the HP network analyzers.
   E-5200 computer, 500 MHz, Pentium III dual processor.
6. Strategic Machine Tool, Inc ($4,350.00):
   Prupose: Lathe used for machining precision parts for the microwave source.
   KLS-1440 geared head precision lathe and accessories.
7. Pearson Electronics, Inc. ($3,179.50):
   Purpose: Current sensors for the backward wave oscillator system
   Pearson current monitor, model # 110, 410, and 2878.
8. L3 Communications, Narda Microwave-East ($2,169.48):
   Purpose: Microwave components for the microwave power and frequency acquisition system.
   503A crystal detector with 4824 replacement diode, 4805 balanced mixer.
9. J. Smith & Assoc. ($763.69):
   Purpose: Microwave connectors and adaptors for the HP network analyzer.
   Various microwave connectors and adaptors.
10. Holman's ($436.00):
    Purpose: HP printer parts which is used for documentation of microwave data.
    C3967A drum unit with C3965A developer unit.
11. Edmund Scientific ($403.25):
    Purpose: Optical mirrors for the high power microwave experiment
    UV enhanced first surface mirrors.
12. Scientific Glass ($190.00):
    Purpose: Parts for a ultra-high vacuum current sensor used in the microwave source.
    Precision glass parts for a current sensor.

Total: $211,346.00
All instrumentation has been purchased, installed and used in our laboratory.

Balance sheet for 3-13391 AFOSR (DURIP)

Code	Date 1	Date 2	Description	Ref #1	Ref #2	Pay Date	Debit	Credit	Balance
3870	04/01/99		Non-capitalized Equipment	Budget 113/827-9219				0.00	$0.00
3870	07/12/99	07/20/99	Pearson Electron/current monitors	pr138867	po 793607	08/03/99	3,175.00	3,175.00	0.00
3870	08/04/99		Pearson Electron/current monitors		po 793607	08/04/99	3,179.50		(3,179.50)
3870	07/12/99	07/21/99	Narda Microwave/misc	pr138869	po 793616		2,155.00	2,155.00	(3,179.50)
	08/19/99		Narda Microwave/misc		po 793616		348.62		(3,528.12)
			Narda Microwave/misc		po 793616	10/18/99	703.62		(4,231.74)
			Narda Microwave/misc		po 793616	10/18/99	763.62		(4,995.36)
			Narda Microwave/misc		po 793616	11/05/99	353.62		(5,348.98)
3870	10/20/99		J. Smith & Assoc.	cr 1299930			103.94		(5,452.92)
3870	11/10/99		J. Smith & Assoc.	cr 1299942			175.55		(5,628.47)
3870	09/28/99		J. Smith & Assoc.	cr 1298210			308.28		(5,936.75)
3870	12/14/99		J. Smith & Assoc.	cr 1301809			156.52		(6,093.27)
3870	01/05/00		J. Smith & Assoc.	cr 1301815			38.41		(6,131.68)
3870	02/15/00		Edmund Scientific	cr 1305429			403.25		(6,534.93)
3870	03/09/00		Scientific Glass	cr 1305439			190.00		(6,724.93)
3870	03/13/00		Holman's	cr 1305440			436.00		(7,160.93)
3870	03/31/00		J. Smith & Assoc.	cr 1301815	corr pending, trf 3-48421			19.01	(7,141.92)
6500	04/01/99		Equipment	Budget 113/827-9219				211,346.00	$211,346.00
6500	07/12/99	07/21/99	Picosecond Pulse/generator	pr138865	po 793617	11/15/99	8,246.00	8,246.00	211,346.00
6500			Picosecond Pulse/generator		po 793617	09/03/99	1,296.00		210,050.00
6500			Picosecond Pulse/generator		po 793617	11/17/99	6,950.00		203,100.00
6500	07/12/99	07/19/99	Hewlett-Packard/network analyzer	pr138866	po 793563	09/20/99	126,910.20	126,910.20	203,100.00
6500			Hewlett-Packard/network analyzer		po 793563	08/17/99	767.00		202,333.00
6500			Hewlett-Packard/network analyzer		po 793563	08/17/99	2,416.50		199,916.50
6500			Hewlett-Packard/network analyzer		po 793563	08/31/99	499.50		199,417.00
6500			Hewlett-Packard/network analyzer		po 793563	08/31/99	4,774.40		194,642.60
6500			Hewlett-Packard/network analyzer		po 793563	08/31/99	9,280.00		185,362.60
6500			Hewlett-Packard/network analyzer		po 793563	09/08/99	48,072.00		137,290.60
6500			Hewlett-Packard/network analyzer		po 793563	09/20/99	58,540.80		78,749.80
6500			Hewlett-Packard/network analyzer		po 793563	09/23/99	2,560.00		76,189.80
6500	07/16/99	08/02/99	Tektronix/oscilloscope	pr138872	po 793953	10/01/99	31,837.73	31,837.73	76,189.80
6500	08/23/99		Tektronix/oscilloscope		po 793953	08/23/99	712.98		75,476.82
6500			Tektronix/oscilloscope			10/14/99	31,124.75		44,352.07
6500	07/21/99	08/26/99	Sci Sales/vacuum leak detector	pr138874	po 794652	36,514.00	28,579.00	101.85	15,874.92
6500	10/29/99	11/05/99	Strategic Machine Tool, Inc.	pr148281	po 796634	11/30/99	4,350.00		11,524.92
6510	04/01/99		Computer Equipment	Budget 113/827-9219				0.00	$0.00
6510	07/19/99	07/27/99	Gateway 2000/E5200 computer	pr138873	po793796	9/15/99	4,383.00		(4,383.00)
6510									(4,383.00)

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cr, 03/13/00

Total Remaining $0.00

Scientific Accomplishments using the Instrumentation

Results shown below present data where an intense relativistic electron beam-driven BWO operates in the single frequency regime at one of two neighboring axial modes. Experiments demonstrated that slight changes of the beam parameters can lead to operation in the cross-excitation regime, where the onset of one mode nonlinearly decreases the start conditions for a neighboring mode, and mode competition results. The scaling of this behavior is consistent with nonlinear simulations presented Levush and colleagues earlier (University of Maryland), and the observations support the validity of those models. We used time-frequency analysis to interpret the frequency output of the source, and it was critical to identifying the coexistence in time between the two axial modes.

Figure 1 presents data representative of operation in the cross-excitation regime for the 12-period SWS. The experimental parameters of this shot are a peak diode voltage ($V_{\mathrm{diode,pk}}$) at the time of microwave generation of 400 kV and an average beam current ($I_{\mathrm{beam,avg}}$) of 1.8 kA. The normalized length for this case is $k_{*}L = 41.3$. Note that microwaves are produced on the rising edge of the UNM long-pulse accelerator voltage, whereas the diode voltage at the start of the microwave pulse is approximately 90% of $V_{\mathrm{diode,pk}}$. As can been seen from Fig. 1, the radiated power initially rises to 22 MW at an output frequency of about 9.1 GHz. Approximately 5 ns after the peak power is reached, the power rapidly decreases as the second axial mode within the SWS begins to grow. It is observed that two modes beat simultaneously for a period of 5 ns, after which point the highest radiated power occurs at a frequency of about 9.5 GHz. This second mode results in a considerably more efficient beam-to-microwave energy conversion.

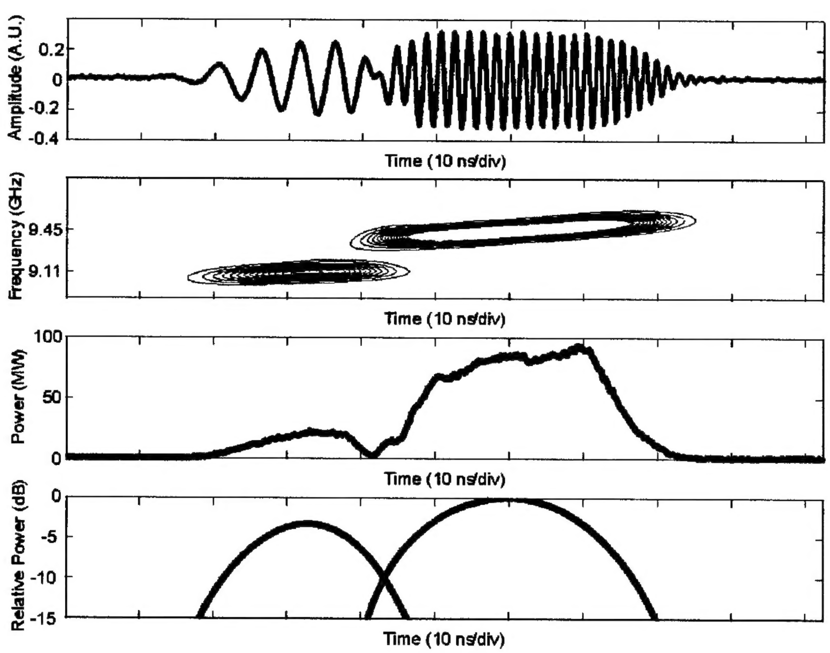

Fig. 1. Evidence of the cross-excitation instability. Top: Heterodyned frequency signal with a LO frequency of 8.9 GHz. Second from top: SPWV time-frequency distribution. Second from bottom: Microwave power. Bottom: Relative power in dB at the two mean frequencies of 9.11 and 9.45 GHz. ($V_{\mathrm{diode,pk}}$ = 400 kV, $I_{\mathrm{b,avg}}$ =1.8 kA, and $k_{*}L = 41.3$, using a 12-period SWS.)

When the diode voltage is decreased to 350 kV, which also decreases the beam current to 1.2 kA, the normalized length $k_* L$ is shifted to 42.3, and the ratio of the beam current to start-oscillation current χ is reduced compared to the previous case. In this single frequency regime (see Fig. 2), the frequency varies slightly from 9.43 to 9.5 GHz owing to an increase of the diode voltage during microwave generation. The maximum radiated power is less than the data shown in Fig. 1 since the beam energy is reduced. In addition, it is evident from Figs. 1 and 2 that the maximum beam-to-microwave energy conversion efficiency in single mode operation is greater than in the cross-excitation regime.

Future work will study the factors that contribute to the temporal coexistence of the modes, yielding some insight into mode saturation and/or electron trapping. Although operation in the cross-excitation regime is less efficient that single frequency operation, it may prove useful to future HPM effects studies.

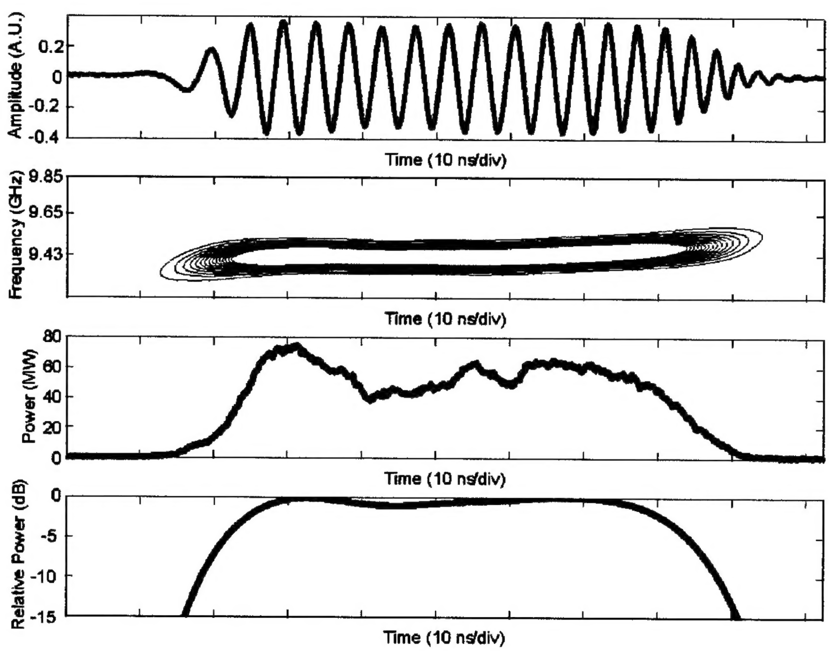

Fig. 2. Data illustrating single mode operation. Top: Heterodyned frequency signal with a LO frequency of 8.9 GHz. Second from top: SPWV time-frequency distribution. Second from bottom: Microwave power. Bottom: Relative power in dB at the mean frequency of 9.43 GHz. ($V_{diode,pk}$ = 350 kV, $I_{b,avg}$ = 1.2 kA, and $k_* L$ = 42.3, using a 12-period SWS.)

Complete details of the scientific accomplishments can be found in the article "Studies of Relativistic Backward Wave Oscillator in the Cross-Excitation Regime," by F. Hegeler, M. Partridge, E. Schamiloglu, and C.T. Abdallah, *IEEE Transaction on Plasma Science Eighth Special Issue on High Power Microwave Generation*, June 2000.

Students Trained using the Instrumentation

The following postgraduate scientists utilized this instrumentation:

1) Dr. Frank Hegeler, Research Assistant Professor
2) Dr. Naz Islam, Research Associate Professor

The following graduate students utilized this instrumentation as part of their research:

1) Gregory Todd Park (M.S. student, graduated in 1999)
2) Robert Wright (Ph.D. student, to graduate in 2000)
3) Kelly Hahn (M.S. student)
4) San Choi (M.S. student)
5) Zhaoxian Zhou (Ph.D. student)

Electrical Engineering students utilized portions of the microwave instrumentation as part of their training in microwaves through the EECE 495/595 Introduction to Microwave course:

Fall 1999: 10 undergraduate students
6 graduate students

Photographs of some of the equipment used by the undergraduate and graduate students in the EECE 495/595 course can be found at our website http://www.eece.unm.edu/microwaves.

In addition, some of the instrumentation will be made available to graduate students of the 553L EECE course, *Experimental Plasma Physics and Pulsed Power*. The equipment will also be incorporated in a series of experiments in a new undergraduate laboratory class on rf techniques for wireless communications.

Future Use of the Instrumentation

The instrumentation acquired under this DURIP project is an integral component of the Pulsed Power and Plasma Science Laboratory's infrastructure. The instrumentation is presently being used in research sponsored by an AFOSR New World Vistas grant.

Presentations and Publications Describing the Utilization of this Instrumentation

1) E. Schamiloglu, F. Hegeler, C. Abdallah, and M. Partridge, "Analysis of the Cross-Excitation Instability in a Relativistic Backward Wave Oscillator, Bull. Am. Phys. Soc., vol. 44, 296, 1999.
2) F. Hegeler, M. Partridge, E. Schamiloglu, and C.T. Abdallah, "Studies of Relativistic Backward Wave Oscillator in the Cross-Excitation Regime," *IEEE Transaction on Plasma Science Eighth Special Issue on High Power Microwave Generation*, June 2000.
3) F. Hegeler, M. Partridge, E. Schamiloglu, C.T. Abdallah, and N. Islam, "Experimental Studies of the Cross-Excitation Instability in a Relativistic Backward Wave Oscillator," to appear in *Proceedings SPIE* (Orlando, FL, April 2000).
4) E. Schamiloglu, F. Hegeler, C.T. Abdallah, and C.G. Christodoulou, "An Overview of Recent Advances in Intense Beam-Driven Relativistic Backward Wave Oscillators and their use in High Power Microwave Effects Studies," presented at EUROEM'2000, Edinburgh, Scotland, June 2000.
5) E. Schamiloglu, F. Hegeler, C.T. Abdallah, K. Hahn, and S. Choi, "Overview of Intense Beam-Driven Relativistic Backward Wave Oscillators and their use in High Power Microwave Effects Studies," presented at ICOPS'2000, New Orleans, LA, June 2000.
6) R.J. Barker and E. Schamiloglu, Eds., *Advances in High Power Microwave Sources and Technologies*, IEEE Press, Piscataway, NJ (to appear 2001).